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CIRCUIT BREAKER DIAGNOSTICS BY VIBRATION MONITORING

David L. Mader

The feasibility of circuit breaker diagnosis with vibration monitoring has been indicated by vibration signature recordings taken on a breaker before and after rehabilitation maintenance. Slight changes are evident in the timing of events and in the level of vibration, showing that valuable mechanical information is present in the signature. Analysis methods are discussed.

INTRODUCTION

The mechanical condition of circuit breakers could be revealed by means of monitoring their vibration during operation. Excessive bearing friction and loose parts have been detected by such monitoring in an Australian research programme. This technique does not require electrical isolation since the vibration sensor is attached to the outside of the breaker shell. For field maintenance purposes a portable instrument could be developed to complement existing instruments like the event recorder now in use. Ultimately, vibration monitoring could be installed permanently and could become part of the protection and control system.

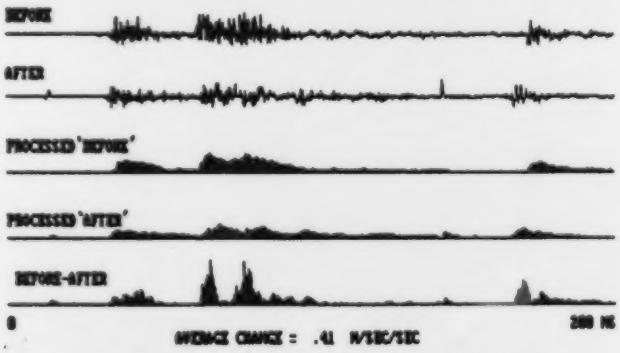

Fig 1. Changes due to maintenance are evident in vibration signatures.

The objective of the present project at Ontario Hydro is to assess the feasibility of the vibration monitoring approach to circuit breaker diagnostics. Our first step was to develop a data acquisition and recording system based on a personal computer so that data analysis could follow

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straight on. In an exploratory experiment, a vibration pickup sensor was attached to a breaker at Leaside TS and vibration waveforms were recorded for several tripping and reclosing operations. This was done on two separate occasions during a scheduled maintenance outage: once before rehabilitation work was done, and once after. No major change in the operation of the breaker was expected, since a major rework of the main drive rod and linkages had previously been done. Nevertheless, slight changes can be seen in Fig 1 in the timing of events and in the vibration levels.

The next step would be to identify promising analysis software packages developed by others and obtain these on a trial basis if available. Otherwise various analysis techniques could be developed in-house.

At the present stage, vibration monitoring of circuit breakers is a research topic. Vibration waveforms taken at a location on the outside shell of the breaker are complicated since all of the moving parts in the breaker are sources of vibration excitation, and since all parts whether fixed or moving can vibrate in response to the excitation. Thus the university research effort described in the literature survey section is aimed at analyzing the waveform to obtain information about the inner workings of the breaker.

Some simple filtering of the Leaside TS waveforms is done in this report to make it clear that the changes introduced by the maintenance work are reflected in the vibration waveforms.

VIBRATION WAVEFORMS FROM LEASIDE BREAKER

Vibration data were taken on an SF_6 circuit breaker, number 34SC11SC, situated at Leaside Transformer Station while the breaker was out of service for rehabilitation maintenance. The maintenance consisted of replacement of a few bearings on the main rod and its linkages, with fiber composition bearings being replaced by steel-oilite bearings. It was thought that the original bearings may have been tight whereas the new bearings were expected to be looser.

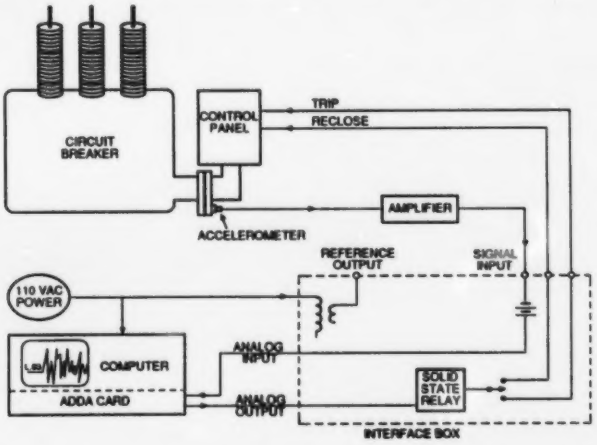


Fig 2. Data acquisition system used analog-to-digital card in a personal computer.

The *before* data with the fiber bearings were taken on May 2, 1988 when the air temperature was 15 C, and the *after* data with steel-oilite bearings were taken on May 20 at 18 C. The effect of temperature on breaker operation is unknown at present. The apparatus described in Appendix I and shown here in Fig 2 was used. The data acquisition program is given in Appendix II. Tripping operations of the breaker are shown in Fig 3 with a set of three operations prior to rehabilitation and three operations afterwards. A 60 Hz signal with 12 cycles is shown to verify that the recording time is 200 ms. Within each set of operations, *before*, and *after*, the waveforms are similar, though they differ in detail.

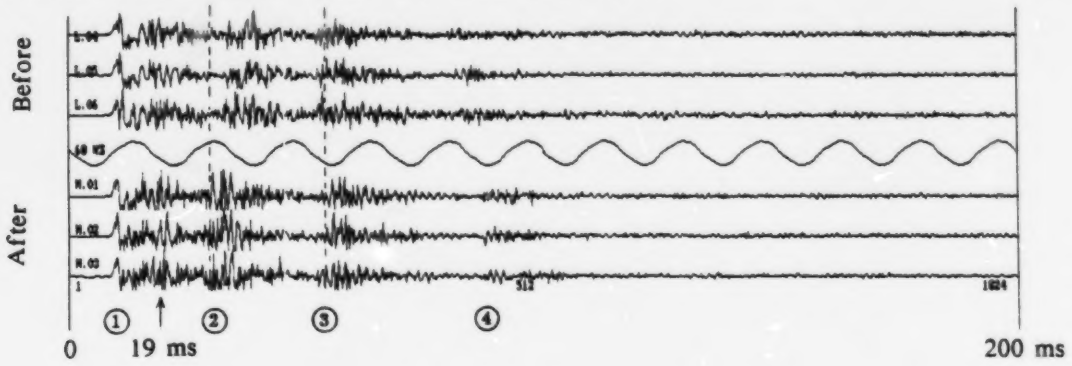


Fig 3. Vibration waveforms seen during tripping operations.

Comparing the *before* and *after* data, a general similarity is noticed. Going into detail in timing, the onset of wave-group 2 occurs earlier in the *after* data, whereas wavegroup 4 occurs later. In amplitude comparisons, the *after* waveforms show higher vibration levels, especially in wavegroups 2 and 3.

It should be noted that the observed waveform is a composite of vibration waves from various vibrating components arriving at the accelerometer. Each wave has its own path to traverse and has its own time of departure, leading to interference between the waves so that they can add or cancel depending on their exact times of arrival at the accelerometer. Thus the differences between two breaker operations can be due to phase variations between waves caused by very minor timing variations. The differences could also be a result of looseness in the mechanism.

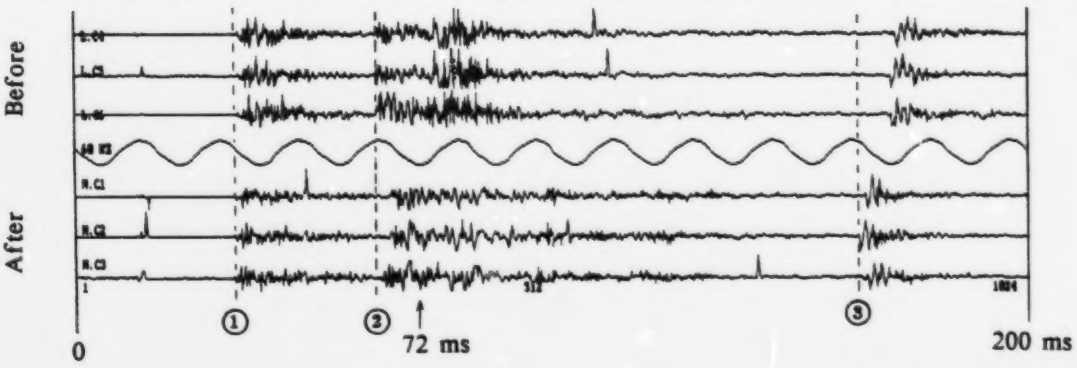


Fig 4. Vibration waveforms seen during reclosing operations.

For comparison, a PROGRAMMA Type TM event recorder used to verify breaker operation after rehabilitation indicated that the contacts opened 19 ms after the trip command. No event recorder readings were available prior to rehabilitation.

Vibration waveforms taken during reclosing operations are collected and shown in Fig 4. An extra burst of vibration that is not present during tripping, wavegroup 3, is present toward the end of the 200 ms time interval. This burst is believed to be due to a latch reclosing. Wavegroup 1 has essentially the timing in the *before* and *after* sets, whereas wavegroup 2 is later and wavegroup 3 is earlier after rehabilitation. In vibration levels, wavegroups 1 and 2 are lower after rehabilitation, in contrast to tripping where vibration levels were higher afterwards. The contact closing time of 72 ms indicated by the event recorder is seen to occur near the onset of wavegroup 2.

Interpretation of the vibration waveforms in detail would require a detailed mechanical analysis of the specific circuit breaker mechanism. Each component has many resonant frequencies and modes of vibration which depend on the component's mass distribution, stiffness and damping characteristics. Many of these modes would be excited appreciably by breaker operation which is impact-like. Then the vibrations from the individual components are transmitted to the sensor through a path which constitutes a filter that modifies the final observed frequency content of the signal.

However, even without an understanding of the underlying circuit breaker mechanism and the various faults that could arise in it, one can characterize the waveforms themselves and seek to discriminate between normal and abnormal circuit breakers. Some simple waveform processing is presented in the next section as a preliminary step toward extracting salient features.

WAVEFORM PROCESSING AND COMPARISON

The raw data consisting of the vibration waveforms seen above are confusing and unreproducible when examined in detail. However, when examined by eye from a distance there are distinguishable and reproducible features such as the burst of vibration in Fig 4 when the latch recloses at 165 ms. What the eye is responding to is an increased vibration level. This can be brought out by computer with the simple processing technique of *detection* and *filtering* illustrated in Fig 5 and given in Appendix III.

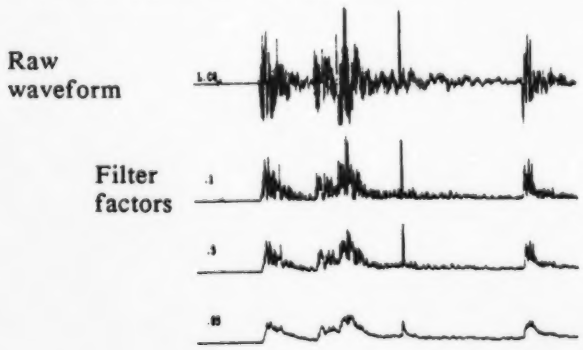
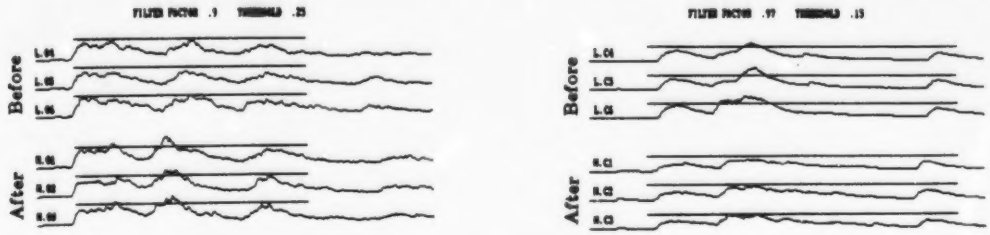


Fig 5. Waveform processing shows vibration level and filters out individual oscillations.

In the traces above of filtered vibration levels the start of an event occurs where the slope becomes steep and positive. The height of the vibration level trace could also contain valuable information.

In detected and filtered traces for the tripping operations shown in Fig 6(a) a filter factor has been specially chosen and a threshold line has been drawn to lie close to but above all three *before* traces. Then the increase in the *after* vibration level mentioned in the previous section is highlighted by the fact that all three of the *after* traces exceed this threshold. Similarly a threshold chosen for the *after* case for reclosing shows in Fig 6(b) that the vibration level was higher *before*.



(a) Trip (b) Reclose

Fig 6. A simple threshold test shows that the breaker has been altered by the maintenance procedure.

In another form of analysis two waveforms are compared by showing the difference between their processed waveforms as seen above in Fig 1 for reclosing and here in Fig 7 for tripping. The average difference is printed out in units of acceleration (meters per second per second) that are independent of the data acquisition system. The final value for the average change could be taken as the first indication that the circuit breaker has changed. Then, more information concerning the nature of the change would be available in the graph of difference versus time.

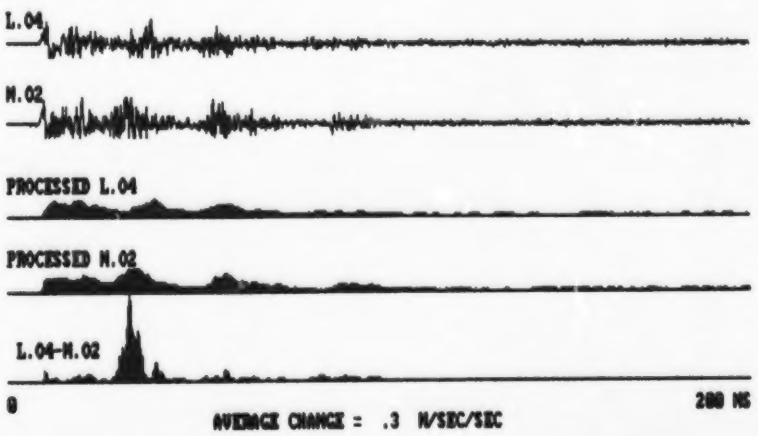
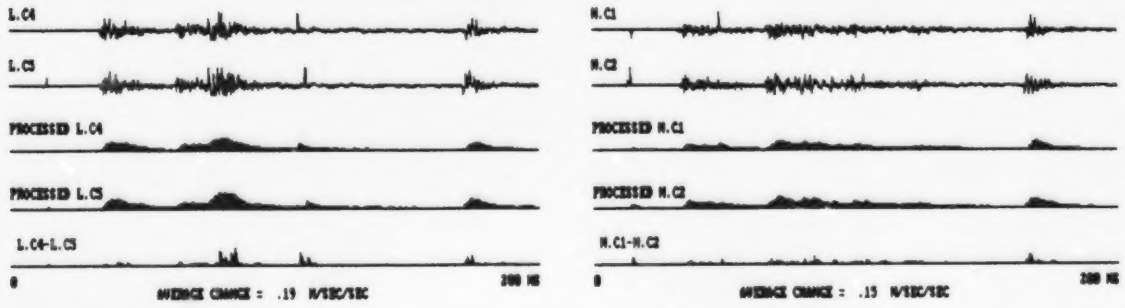


Fig 7. Change of tripping waveform is displayed in difference plot.

There are of course also differences between waveforms taken under nominally the same conditions. The difference analysis for two waveforms taken before maintenance is shown in Fig 8(a) and that for two taken after is given in (b).



(a) Before maintenance (b) After maintenance

Fig 8. Comparison of reclosing waveforms taken under the same conditions.

Note that the spikes in Fig 8(a) occur at different times and both show up in the difference plot. They both have the same sign because what is being plotted is not the difference but the square of the difference. It is also the square of the point by point differences which is accumulated to arrive at the global average change.

LITERATURE SURVEY

An analysis technique developed by Timbs at the University of Sydney in Australia is called cumulative spectral analysis/1/. In this technique the onset of an event such as a moving rod contacting a bumper is detected as the starting time for a mathematical decaying sine wave which is fitted to a portion of the data in the waveform.

Lai et al at the University of Buffalo have applied a pattern recognition technique to circuit breaker vibration waveforms/2/. In general terms this technique first requires design of a feature extractor, which is application specific. Then a general classifier is used to compare the features with reference features and to make a decision. The method was applied under laboratory conditions to several breakers with a variety of defects introduced artificially and was able to discern between normal and abnormal breakers.

A general paper by Yen/3/ on the analysis of acoustical signals shows how a vibration waveform could be treated to bring out the features in terms of specific frequencies being present at specific times. This paper shows a waveform received from a simulated submarine pinged with sonar that bears at least a superficial resemblance to the circuit breaker waveforms given by Timbs/1/. The analysis consists of calculating the Wigner distribution function and then identifying the peaks in this function. Such peaks would correspond to the "events" of Timbs or could be used for the "features" needed by Lai.

CONCLUSIONS

The feasibility of performing circuit breaker diagnostics with vibration monitoring has been shown at a preliminary stage. The vibration signature of a circuit breaker has been recorded with a computer before and after rehabilitation maintenance. Slight changes are evident in the timing of events and in the level of vibration, showing that mechanical information is present in the signature.

Future work could advance on several fronts. The data acquisition system could be expanded to record waveforms from three accelerometers, one for each of the electric power phases, and a faster analog to digital converter with a large memory could be used for more data points. The system would need to be packaged in a compact and hardened version for field use. A data base could be built up by taking vibration signatures on a number of breakers. Turning to data analysis, the simple method given in this report could be expanded to provide a printout about the peaks seen in the difference plot. The algorithms developed in the referenced literature should be explored to assess their usefulness.

The author thanks S.M. Kramer, Metallurgical Research, for a copy of the paper by Yen on the Wigner function, M.G. De Montmorency, Mechanical Research, for the loan of an accelerometer and charge amplifier for initial work, and J.J. Liska, Mechanical Research, for useful comments on machine dynamics.

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1. Timbs, L., "Mechanical condition monitoring of circuit breakers," A thesis submitted for the degree of Master of Engineering Science, University of Sydney, Australia, November 21, 1987.

2. Lai, M.L., Park, S.Y., Lin, C.C., Naidu, H., Soom, A., Reinhorn, A.M., Lee, Y.H., Soong, T.T., Demjanenko, V., Benenson, D.M. and Wright, S.E., "Mechanical failure detection of circuit breakers," to be presented at IEEE PES Winter Power Meeting in 1988.

3. Yen, A., "Time and frequency representation of acoustic signals by means of the Wigner distribution function: Implementation and interpretation," J. Acoust. Soc. Am. **81** (6), pp. 1841-50, June 1987.

APPENDIX I - DATA ACQUISITION SYSTEM

The vibration signature from a circuit breaker is a transient waveform and so differs from that of a rotating machine which produces a repetitive waveform. Thus vibration acquisition and analysis equipment developed for rotating machines is not appropriate for circuit breakers. Traditionally an oscilloscope would be used to record waveforms and a permanent record would consist of a photograph of the screen. More recently, digital oscilloscopes have become established as a means to record and save a transient event. These scopes can be interfaced to a computer so that the computer's mass storage capability can be used to store waveforms permanently.

A further development is the general introduction of data acquisition peripherals for personal computers. These can often be less expensive than digital scopes and can circumvent the need to interface the scope to the computer. (A GPIB interface kit for a Tektronix scope cost $1500 for the interface alone and was temperamental to use.) One of the more recent products is a four channel transient recorder ($2000 US) which can digitize at a rate of up to 500 kHz and can store up to 64,000 data points in its own memory. Then after the transient has occurred the computer can interrogate the recorder's memory at leisure. What was used for the work in this report was a low speed AD converter ($300) alone on a card with no local memory. For each data point the signal is digitized, is read by the computer, and is stored in computer memory before the next data point is taken.

The data acquisition equipment for this report consisted of:

1. A vibration pickup sensor attached to the outside of the breaker. It was a Bruel & Kjaer model 4384 accelerometer with a mounted resonant frequency of 42 kHz and an output flat to within 10% up to 12 kHz. (Cost $900.) The accelerometer was screwed onto an Endevco #2988 cementing stud which was epoxied onto a flange joining the main rod housing to the control unit. The accelerometer was removed between tests, but was believed to be reproducibly remounted for the second test.

2. An amplifier. This was a Bruel & Kjaer model 2635 Charge Amplifier (Cost $4400), which is a small battery powered unit that does signal conditioning and amplification for piezoelectric accelerometers. This unit along with the above accelerometer provides a voltage output which is calibrated in terms of acceleration.

3. An AD (analog-to-digital) converter. This was an ADDA 12 bit PC card which plugs into a slot in an IBM compatible personal computer and which can digitize an input analog voltage to 12 bits yielding a precision of one part in 4096. (Cost $300.) The DA (digital to analog) capability of this card was used for computer output, to trigger the circuit breaker.

4. A personal computer. A portable Compaq 286 computer was used to host the ADDA card and operate it, and to store and display the vibration waveforms. The computer also operated the circuit breaker and thereby synchronized trip/reclosing commands with data acquisition. Waveforms could be stored permanently on the computer's built-in hard disk and could also be archived on floppy diskettes.

   Data analysis and decision making would be done on the same computer in future developments.

5. A data acquisition program for the computer. The program, given in Appendix II, was specially written for the application. The code to operate the ADDA card was provided by its manufacturer and is incorporated in the program.

6. An interface box. A special purpose box was built in-house to interface from the ADDA card to the accelerometer amplifier and to the circuit breaker, and to provide a time reference signal. The interface from the amplifier consisted of a 3 V battery to offset the bipolar amplifier output to unipolar values acceptable to the AD converter. A solid state HEX-FET relay was used to fire the circuit breaker from the computer. This relay was turned on by the DA output from the ADDA card, under program control. The relay contacts were connected to the 250 VDC control circuit in the breaker control panel by jumper wires, with a pair of wires for trip and a pair for reclose.

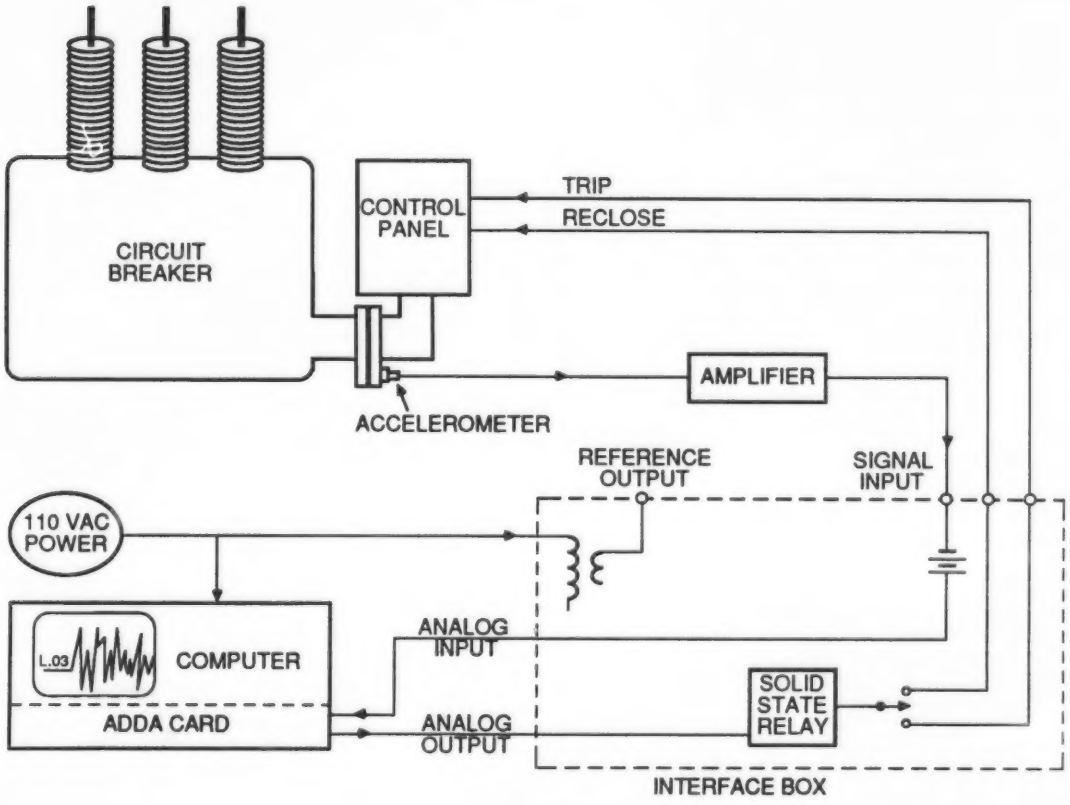

Fig 9. Apparatus

APPENDIX II - DATA ACQUISITION PROGRAM

This BASIC program was compiled with Z-Basic and was used with an analog to digital/digital to analog board in a Compaq 286 personal computer with an 8 MHZ clock. Execution time was fast enough to record up to 6360 points per second, which would correspond to an upper frequency limit of approximately 3 kHz. The accelerometer amplifier was set to an upper frequency limit of 3 kHz.

```
00010 CLS
00020 PRINT "Program CAPTURE"
00030 port%=&H278 : port1%=port%+1 : port2%=port%+2 : port3%=port%+3
00040 port4%=port%+4 : port5%=port%+5 : port6%=port%+6 :port7%=port%+7
00050 REM  turn relay off via (high) power-on level
00060 OUT port6%,0 : REM  lowbyte= 0
00070 OUT port7%,15 : REM highnibble=15
00080 DIM D%(20000)
00090 PRINT "   Scope on a board using ECS's 12 bit AD-DA card for PC"
00100 PRINT "   Analog input on channel 0, pin 5 (gnd - pin 1)"
00110 PRINT "Press space bar to leave waveform display"
00120 N%=1024 : delay%=6 :  SCALE!=.15 : THRESHOLD%=0 : SCAN!=0
00130 PRINT"N, delay, SCALE ";N%;" ";delay%;" ";SCALE!
00140 INPUT"  ? Want to change these (Y)  Q to quit ";C$
00150 IF C$="Q" OR C$="q" THEN END
00160 IF C$><"Y" AND C$><"y" THEN GOTO 200
00170 INPUT"? Number of data points (1024 max.) ";N%
00180 INPUT"? Number of iterations in delay loop (e.g. 6 for 1024 points in 200ms ";delay%
00190 INPUT"? Scale factor (e.g. 0.15) ";SCALE!
00200 GOSUB 380 : REM  * fire circuit breaker *
00210 GOSUB 520 : REM  * Digitize *
00220 REM  turn relay off via high level
00230 OUT port6%,0 : REM  lowbyte= 0
00240 OUT port7%,15 : REM highnibble=15
00250 X1%=1 : X2%=N% : REM  X1 and X2 are indices in D
00260 GOSUB 590 : REM * Plot *
00270 INPUT"? Want to zoom (Y) ? ";C$
00280 IF C$ >< "Y" AND C$ >< "y" THEN GOTO 310
00290 INPUT"? Start X (min 1), stop X (max 1024)  ";X1%,X2%
00300 GOSUB 590
00310 INPUT @(60,24) "? Zoom again (Y) ? ";C$
00320 IF C$="Y" OR C$="y" THEN CLS : GOTO 290
00330 MODE 4 : REM  Restore normal screen
00340 GOSUB 690 : REM * Save on disk *
00350 INPUT "? Fire CB and acquire new waveform (Y) ? ";C$
00360 IF C$="Y" OR C$="y" THEN CLS : GOTO 130
00370 END
00380 REM ********************** Fire relay ************************************
00390 INPUT"Press ENTER to fire   Q to quit ";C$
00400 IF C$="Q" OR C$="q" THEN END
00410 REM  using D to A output to solid state DC relay (Hex FET) via transistor
00420 REM  The interface box has a transistor to invert the output from the
```

```
00430 REM  D/A, so high D/A means solid state relay OFF.
00440 REM  low D/A output means solid state relay is ON.
00450 REM  The reason for inverting is because the D/A board powers up in the
00460 REM  high state. So the circuit breaker could fire when the computer is
00470 REM  turned on, if everything else was first on.
00480 REM  D/A full output is 9V for 4095
00490 OUT port6%,0 : REM  lowbyte
00500 OUT port7%,0 : REM highnibble
00510 RETURN
00520 REM ********** Digitize **************************************
00530 FOR J%=1 TO N%
00540 OUT port%,0:OUT port3%,0:FOR I=1 TO 7:A%=INP(port4%):NEXT:FOR I=1 TO 7
      :A%=INP(port5%):NEXT
00550 D%(J%)=(INP(port2%) AND 15)*256+INP(port1%)
00560 FOR I%=1 TO delay% : NEXT I%
00570 NEXT J%
00580 RETURN
00590 REM ********** Plot waveform **************************************
00600 MODE 7
00610 XS%=INT(1024/(X2%-X1%))
00620 M%=X1%
00630 FOR J%=0 TO 1022 STEP XS% : REM  uses full Z-Basic screen 0 to 1023
00640 PLOT J%,INT(D%(M%)*SCALE!) TO J%+XS%,INT(D%(M%+1)*SCALE!)
      : REM points are connected by lines
00650 M%=M%+1
00660 NEXT J%
00670 IF INKEY$="" THEN GOTO 670 : REM  keep display uncluttered for screen dump
00680 RETURN
00690 REM ********** Save waveform on disk ******************************
00700 INPUT"? Want to store on disk (Y) ";C$
00710 IF C$ >< "Y" AND C$ >< "y" THEN RETURN
00720 INPUT"? filename  ";C$
00730 OPEN "R",1,C$
00740 PRINT#1,N% : PRINT#1,delay% : PRINT#1,4095
      : PRINT#1,THRESHOLD% : PRINT#1,SCAN!
00750 REM  save scale!=4095 for ZPLOT, for 12 bit digitizer
00760 FOR J%=1 TO N% : PRINT#1,D%(J%) : NEXT
00770 CLOSE#1
00780 RETURN
```

Fig 10. An accelerometer waveform for 100 ms of a tripping operation.

APPENDIX III - ANALYSIS PROGRAM

Program DIFFERENCE uses detected waveforms with filtering and takes the difference squared between vibration levels and plots them. It calculates the overall difference as a global measure of change. This BASIC program is written for use with Z-Basic.

```
10 CLS
20 DIM D%(1024,9),SCALE!(9),C$(9),DCOFFSET!(9),A%(1024,9)
30 DIM SENSITIVITY!(9),CAL!(9)
40 PRINT "Program DIFFerence "
50 PRINT "  Uses detected waveform with filtering"
60 PRINT "  Takes difference between vibration levels and plots"
70 PRINT "Calculates overall difference as global measure of change"
80 PRINT "      Press space bar to leave waveform display"
90 X1%=1 : X2%=1024
100 PRINT " Start and end points ";X1%;" ";X2%
110 NW%=5 : REM  plotting five traces
120 FF!=.9 : REM  filter factor
130 GOSUB 770 : REM * Get two raw waveforms from disk *
140 YSEPARATIUN%=INT((744-62)/(NW%))
150 REM  Screen Y is 744 dots. One line of print is 35 dots high. Have 2 lines
160 GOSUB 960 : REM  Process waveforms
170 GOSUB 230 : REM * Plot five traces *
180 MODE 4 : REM  Restore normal screen
190 PRINT "? Read waveforms from disk again (Y), otherwise end "
200 C$=INKEY$ : IF C$="" THEN 200
210 IF C$="Y" OR C$="y" THEN GOTO 110
220 END
230 REM ********************** plot traces ***************************
240 MODE 7
250 REM **** plot raw waveforms ****
260 FOR IW%=1 TO 2
270 DY%=INT(YSEPARATIUN%*(IW%))
280 IF IW%=1 THEN DY%=DY%+2
290 PSCALE!=-(744-62)*.5/SCALE!(IW%)/NW% : REM Inverts. Z-Basic screen Ymax=744
300 PR%=INT(24!/744!*(DY%-YSEPARATIUN%/2+PSCALE!*DCOFFSET!(IW%)))+1
310 PRINT @(0,PR%) C$(IW%);
320 XS%=INT(1024/(X2%-X1%))
330 M%=X1%
340 FOR J%=0 TO 1022 STEP XS% : REM  uses full Z-Basic screen 0 to 1023
350 PLOT J%,INT(D%(M%,IW%)*PSCALE!)+DY%
      TO J%+XS%,INT(D%(M%+1,IW%)*PSCALE!)+DY% : REM points are connected by lines
360 M%=M%+1
370 NEXT J%
380 NEXT IW%
390 REM **** plot detected and filtered waveforms ****
400 FOR IW%=1 TO 2
410 PSCALE!=-(744-62)/SCALE!(1)/NW% : REM  - sign inverts
420 DY%=INT(YSEPARATIUN%*(IW%+2))
430 IF IW%=1 THEN DY%=DY%-1
```

```
440 PR%=INT(24!/(744!-62!)*(DY%-YSEPARATIUN%/2))
450 PRINT @(0,PR%) "PROCESSED ";C$(IW%);
460 XS%=INT(1024/(X2%-X1%))
470 M%=X1%
480 FOR J%=0 TO 1022 STEP XS% : REM  uses full Z-Basic screen 0 to 1023
490 Y1=INT(A%(M%,IW%)*PSCALE!)+DY%
500 PLOT J%,DY% TO J%,Y1 : REM   fill in graph solid
510 M%=M%+1
520 NEXT J%
530 NEXT IW%
540 REM **** plot difference SQUARED ****
550 CHANGE!=0!
560 PSCALE!=-(744-62)/SCALE!(1)/NW% : REM  - sign inverts
570 DY%=INT(YSEPARATIUN%*(5)) : REM  (5) for the fifth trace
580 PR%=INT(24!/(744!-62!)*(DY%-YSEPARATIUN%/2)) -1
590 PRINT @(1,PR%) C$(1);"-";C$(2)
600 XS%=INT(1024/(X2%-X1%))
610 M%=X1%
620 FOR J%=0 TO 1022 STEP XS% : REM  uses full Z-Basic screen 0 to 1023
630 DELTA!=(A%(M%,1)*CAL!(1)-A%(M%,2)*CAL!(2))^2 : REM  calibrated in m/sec/sec
640 CHANGE!=CHANGE!+DELTA!
650 Y1=INT(DELTA!*PSCALE!)+DY%
660 PLOT J%,DY% TO J%,Y1 : REM  solid fill
670 M%=M%+1
680 NEXT J%
690 PRINT @(74,23) "200 MS"; : REM ; to disable carriage return
700 PRINT @(0,23) "0";
710 AVE!=INT(100*SQR(CHANGE!)/(M%-X1%)) : AVE!=AVE!/100
      : REM a few decimal places
720 PRINT @(22,24) "AVERAGE CHANGE = ";AVE!;" M/SEC/SEC";
730 IF INKEY$="" THEN GOTO 730 : REM  keep display uncluttered for screen dump
740 REM  Width of screen for PRINT is 76 characters.
750 REM  More means carriage return/line feed even with ;
760 RETURN
770 REM  ********** Retrieve waveforms from disk **********
780 PRINT "Reading waveforms from disk"
790 FOR IW%=1 TO 2
800 SUM!=0!
810 INPUT "? filename  ";C$(IW%)
820 OPEN "I",1,C$(IW%)
830 INPUT#1,N% : INPUT#1,DULAY% : INPUT#1,SCALE!(IW%)
840 INPUT#1,SENSITIVITY!(IW%) : INPUT#1,SCAN!
850 REM scale! is max value from digitizer: 4095 for 12 bits, 255 for 8 bits
860 FOR J%=1 TO N% : INPUT#1,D%(J%,IW%) : NEXT
870 CLOSE#1
880 FOR J%=1 TO 50 : SUM!=SUM!+D%(J%,IW%) : NEXT J%
890 DCOFFSET!(IW%)=SUM!/50!
900 REM  calibrate values in digitized waveform in terms of acceleration
910 REM  dc offset is series battery voltage, 3.21 V measured
920 DIG_VOLT!=DCOFFSET!(IW%)/3.21 : REM  digits per volt
```

```
930 CAL!(IW%)=1!/( DIG_VOLT! * SENSITIVITY!(IW) ) : REM  m/sec/sec per digit
940 NEXT IW%
950 RETURN
960 REM ********************** Process waveforms ****************************
970 REM  Simple measurement of activity in the waveform is the detected
980 REM  level of the waveform, in the sense of an AM radio receiver.
990 REM  Rectifify the waveform via ABS( ).
1000 REM  Low pass filter with filter factor FF
1010 PRINT "Processing waveforms  -  please wait"
1020 FOR IW%=1 TO 2
1030 DETECTED!=0!
1040 FOR J%=1 TO N%
1050 ABDUFF!=ABS(D%(J%,IW%)-DCOFFSET!(IW%)) : REM  data - dc offset
1060 DETECTED!=DETECTED!*FF!+ ABDUFF!*(1!-FF!)
1070 A%(J%,IW%)=DETECTED!
1080 NEXT J%
1090 NEXT IW%
1100 RETURN
```

FILTER FACTOR = .9 AVE. CHANGE = .4 M/SEC/SEC